# AN OVERVIEW OF GEOLOGIC SEQUESTRATION OF $CO_2$

Sally M. Benson
Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California 94720
Smbenson@lbl.gov, 510-485-5875

**Abstract**
This paper presents an overview of geologic sequestration of $CO_2$. Topics addressed include the nature and extent of formations that could be used for geologic sequestration, the physical and chemical processes responsible for geologic sequestration, pilot-scale and demonstration projects underway today, issues that need to be addressed to advance the technology and fundamental research needs to support implementation of this carbon sequestration strategy.

KEYWORDS: Sequestration, Carbon, Geologic Formations, Climate, $CO_2$

**Geologic Sequestration Concept**
Four principle types of geologic formations are widespread and have the potential for sequestering large amounts of $CO_2$:

- Active and depleted oil;
- Active and depleted gas reservoirs;
- Brine formations; and
- Deep coal seams and coalbed methane formations.

Other geologic formations such as marine and arctic hydrates, $CO_2$ reservoirs, mined cavities in salt domes and oil-shale may increase sequestration capacity or provide niche opportunities but are likely to be developed only after the easier sequestration targets are explored.

The conceptual framework and opportunity for sequestration of $CO_2$ in brine formations and depleted oil and gas formations were presented in early papers by Koide et al., 1992, 1993, 1998; Winter and Bergman, 1993; van der Meer, 1992, 1993; Gunter et al., 1993; Hendriks and Blok, 1993, 1995; Holloway and Savage, 1993; Holt et al., 1995; Bachu et al., 1994; Bergman and Winters, 1995; Omerod, 1994; and Weir et al., 1995. In 1996, Gunter et al. described a process by which coalbed methane production could be enhanced while simultaneously sequestering $CO_2$. Studies by Byrer and Guthrie (1997, 1998) and Stevens et al. (1998a,b) suggest that worldwide and in the U.S., $CO_2$ assisted coalbed methane recovery will significantly add to the capacity for geologic sequestration of $CO_2$.

Currently, it is broadly accepted that $CO_2$ can be sequestered in geologic formations by three principal mechanisms (Hitchon, 1996):

- $CO_2$ can be trapped as a gas or supercritical fluid under a low-permeability caprock, similarly to the way that natural gas is trapped in gas reservoirs or that gas is stored in aquifer gas storage. This process is commonly referred to as hydrodynamic trapping and, in the short term, is likely to be the most important mechanism for sequestration.
- $CO_2$ can dissolve into the fluid phase. This mechanism is referred to as solubility trapping. In oil reservoirs this lowers the viscosity and swells the oil, which provides the basis for one of the more common EOR techniques. The relative importance of solubility trapping depends on a large number of factors, such as the sweep efficiency of $CO_2$ injection, formation of fingers, and the effects of formation heterogeneity.
- $CO_2$ can react, either directly or indirectly, with the minerals and organic matter in the geologic formations to become part of the solid mineral matrix. Formation of carbonate minerals such as calcite or siderite and adsorption onto coal are examples of mineral trapping. Developing methods for increasing mineral trapping will create stable repositories of carbon that are unlikely to return to the biosphere and that decrease safety hazards associated with unexpected leakage of $CO_2$ to the surface.

Several worldwide and national assessments of the storage volume available for sequestration demonstrate the significant potential for geologic sequestration of $CO_2$ in brine formations, coal formations, and depleted oil and gas reservoirs (Omerod et al., 1994). Subsequent studies have focused on assessing important aspects of regional geologic formations that may be suitable for sequestration (Tanaka et al., 1995; Gunter et al., 1996; Gupta et al., 1998; Sass et al., 1998; Liu et al., 1998; Bachu and Gunter, 1998; McKean et al., 1998; and Hattenbach et al., 1998).

The idea that $CO_2$ could be separated from flue gases and sequestered from the atmosphere emerged in the open literature in the late 1970s (Marchetti, 1977; and Baes et al., 1980). However, it was not until the early 1990s that R&D in $CO_2$ sequestration began in earnest. Since that time, however, progress has been accelerating through a combination of industrial, academic, and public-sector efforts. A number of R&D and demonstration projects exploring sequestration options such as ocean disposal, ocean fertilization, reforestation, soil carbon enhancement, and geologic sequestration have begun during the past decade. Among these options, geologic formations are likely to be the first large-scale target for sequestration of $CO_2$ from point sources such as power plants or large industrial facilities. A number reasons can be cited for this view:

- Industrial experience in the oil, gas, and gas-storage industry can provide the expertise and technology needed to enable rapid commercialization of this approach.
- Several collateral economic benefits are possible, including $CO_2$-enhanced oil and gas recovery and enhanced coalbed methane recovery.
- Suitable geologic formations, including oil, gas, brine, and coal formations are located across the U.S.
- The regulatory infrastructure associated with injection into oil and gas formations is well established, enabling rapid application of sequestration technologies in these types of formations.
- Geologic analogs such as natural $CO_2$ reservoirs prove that geologic structures can sequester $CO_2$ over very long times.
- Public acceptance for geologic sequestration will grow as technological advances lead to innovative methods for creating permanent mineral sinks for $CO_2$.

**Current Pilot and Demonstration Projects of Geologic Sequestration**

Recent years have seen rapid progress in geologic sequestration. Korbol and Kaddour (1995) described Statoil's Sleipner Vest project, which is the first $CO_2$ sequestration project in a brine formation. This project, which has now been underway for nearly 3 years, has demonstrated that one million tonnes per year of $CO_2$ can be separated from natural gas produced in the North Sea and injected into a subsea brine-filled sandstone formation at a depth of 800 m. A 3-dimensional seismic survey has now been completed and has provided extremely valuable information on the rate and direction of $CO_2$ migration.

Progress is also being made in sequestering $CO_2$ in oil formations. This option is comparatively attractive because of the opportunity to offset the cost of sequestration by $CO_2$ EOR. Currently, the cost for capture and separation of $CO_2$ from power plant flue gases is usually not competitive with natural sources; however, under some circumstances and with improved separation technology, this may become a preferred source of $CO_2$ for EOR. The oil and gas industry has nearly three decades of experience from nearly 70 EOR projects worldwide (Moridis, 1998a,b). This experience is invaluable and is likely to provide the technology needed to advance sequestration technology in all types of geologic formations. Two demonstration projects are underway or in the planning phase. In October 2000, Pan Canadian Resources plans to begin injecting $CO_2$ separated from a coal gassification plant in North Dakota into the Weyburn Field, a fractured carbonate reservoir for EOR (Hattenbach, et al., 1998). In addition, BP-Amoco is developing a demonstration project for $CO_2$ EOR on the North Slope of Alaska in the Schrader Bluff field, using $CO_2$ separated from gas turbine exhaust gas (McKean et al., 1998).

Two pilot projects of enhanced coalbed methane production using $CO_2$ injection are also underway in North America, one in the San Juan Basin, New Mexico, and one in the Alberta Basin, Canada (Stevens et al., 1998; and Gunter, personal communication). Field-scale experience gained from these pilot projects will be valuable in assessing the sequestration potential associated with enhanced coalbed methane recovery and for developing methods to co-optimize sequestration and EGR.

**Applied R&D to Advance Geologic Sequestration**

In parallel with these above-mentioned R&D and demonstration projects, the U.S. DOE has sponsored or conducted several major R&D planning activities (DOE, 1993; Benson et al., 1997; Carbon Sequestration:

State of the Science draft; DOE, 1998; and FETC, 1999). All of these R&D planning activities have included significant industrial and academic involvement. The most recent of these, prepared by FETC (1999), describes an R&D program with the overall goal to "reduce the cost of carbon sequestration to $10 net per ton of carbon emissions avoided or lower by the year 2015." The strategy outlined in this plan envisions

> "…two complementary phases for its technology products. In the mid-term, the program will develop options for value-added sequestration with multiple benefits, such as using Enhanced Oil Recovery operations and in methane production from deep, unminable coal seams. In the long term, the technology products will be more revolutionary and rely less on site-specific or application specific factors to ensure their viability."

R&D needs that are specific to sequestration in geologic formations have been identified and can be grouped broadly into the following goals.

1. <u>Lower the cost and energy requirements of geologic sequestration.</u>
Cost estimates for geologic sequestration by IEA Greenhouse Gas R&D program (1994) and Herzog (1998) indicate that over 75% of the costs of geologic sequestration are associated with separation and capture, compression, and transportation, rather than the well-field operations themselves. Nevertheless, there are opportunities to lower the net cost of sequestration by optimizing the geologic sequestration system. These opportunities include:

- Offsetting the cost of sequestration with value-added benefits such as EOR or EGR.
- Lowering the overall cost by sequestering less pure $CO_2$ waste streams that are less expensive or require less energy to separate from flue gas.
- Minimizing $CO_2$ transportation and compression costs by identifying sequestration sites that are close to the $CO_2$ generator.
- Identifying opportunities for cost reduction by developing and applying engineering and economic models that link separation, compression, transportation, and the geologic sequestration system.

2. <u>Identify and demonstrate reliable and cost-effective systems for monitoring $CO_2$ migration in the subsurface.</u>
Monitoring has been identified as one of the highest priority needs in several industry, academic, and government-sponsored workshops that have taken place over the past year (DOE, 1998; BP-Amoco, 1999; Pan Canadian Resources, 1999; Harvard University, Kennedy School of Government, 1999; MIT, 1998; and Columbia University, 1998). Monitoring $CO_2$ migration in the subsurface plays several diverse and critical roles in the development and acceptance of geologic sequestration. First, it is essential for accounting purposes. That is, it will be necessary to verify the net quantity of $CO_2$ that has been sequestered in the subsurface. Second, it is necessary for monitoring sweep efficiency and determining whether the available sequestration capacity is being used effectively. Third, it is needed for optimizing EOR and enhanced coalbed methane recovery. Finally, it is necessary to ensure the safety of sequestration projects by demonstrating that the $CO_2$ is retained in the formation into which it was injected. Monitoring approaches are likely to be crosscutting, with some level of refinement for the different types of formations. Methods are needed to assess all three trapping mechanisms: hydrodynamic, solubility, and mineral. Methods for monitoring hydrodynamic trapping are the best developed and build on decades of experience gained in the oil and gas industry. Significantly more R&D will be required to develop reliable methods for monitoring solubility and mineral trapping. Potential monitoring methods include:

- Surface monitoring of rates and compositions of injected and produced gases and liquids.
- Surface (including 3-D seismic methods), surface-to-borehole, single-well, and cross-borehole time-lapse seismic methods.
- Electrical methods such as electrical resistance tomography and crosswell electromagnetic methods.
- Reservoir pressure and temperature measurements.
- Natural and introduced chemical tracers that will provide additional information needed to quantify hydrodynamic, solubility and mineral trapping rates and processes.

3. Enhance, develop, and verify subsurface transport models for predicting, assessing, and optimizing the performance of $CO_2$ sequestration in geologic formations.
Computational models that can be used to predict, assess, and optimize geologic sequestration are among the most important enabling technologies for geologic sequestration. Nearly three decades of industrial experience in the oil and gas, groundwater, gas storage, and environmental remediation sectors have led to the development of many models that are used routinely for predicting migration of fluids and gases underground. Among these models, those used to simulate $CO_2$ flooding (e.g., ECLIPSE™, STARS, UTCOMP, and VIP™ Therm) and $CO_2$-enhanced coalbed methane recovery are the most directly relevant to geologic sequestration. However, several other models (e.g., TOUGH2, TOUGHREACT, and NUFT) include the multiphase, multicomponent transport processes and some of the chemical reactions that are needed to simulate sequestration in brine formations. In practice, all of these models have been used with good success. The success of these models, however, is based on extensive calibration, history matching, and relevant experience from related applications. Developing reliable models for geologic sequestration will require similar levels of practical experience. The most efficient approach and the approach that is most likely to lead to early acceptance on the part of industry and regulators is the enhancement of existing models to include additional chemical and physical processes that are important for sequestration. Critical needs for model enhancement include:

- Reliable, scientifically based approaches for predicting solubility and mineral trapping in subsurface transport, including the adsorption/desorption processes associated with enhanced coalbed methane recovery.
- Reliable, scientifically based approaches for modeling the phase behavior of $CO_2$, oil, and brine around the critical point.
- Sensitivity studies to identify the most important input variables for predicting and optimizing geologic sequestration.
- Application to and testing of these models on real-world problems.
- Systematic code intercomparison and verification studies to enhance confidence in the reliability of these computer models.

4. Develop better capacity estimates and screening criteria for brine and coalbed methane formations to help $CO_2$ generators, sequesterers, and regulators identify formations that are suitable for sequestration on a regional basis.
Significant improvements in capacity assessment are needed to advance geologic sequestration. Worldwide estimates of the sequestration capacity of geologic formations are large, ranging from 100 to 3000 GtC (Omerod, 1994). Nationally, the range is also large and in need of refinement. For example, in the U.S., the Mt. Simon brine formation has an estimated capacity of 40 to 220 GtC (Gupta et al., 1998). Natural gas fields have from 10 to 25 GtC capacity (Robert Burruss, personal communication), and an estimated 2.3 GtC could be sequestered in the coalbed methane formation in the San Juan Basin (Stevens and Kuuskraa, 1998). Estimates on a national or regional basis, however, are highly uncertain and depend heavily on the approach taken and on assumptions used in the analysis (Bergman and Winter, 1995; Winter and Bergman, 1995; and DOE, 1998). Moreover, it is important not only to account for the storage volume available for sequestration, but also to determine what fraction of the available storage space will be occupied by $CO_2$. This will depend strongly on the heterogeneity of the formation and the complex interplay of viscous and gravitational forces. For example, studies by van der Meer (1996) suggest that only 1% to 6% of the storage volume in porous formations will be occupied with $CO_2$. Additional regional investigations are needed to refine capacity estimates. This should be accompanied by a systematic effort to develop screening criteria that will help $CO_2$ generators and regulators and the sequestration industry select the best sites for geologic sequestration.

**Fundamental Research to Enhance Implementation of Geologic Sequestration**
In addition to the applied R&D needs addressed above, there are also fundamental research questions that could, if addressed, enhance the scientific foundation for long term geologic sequestration. New and improved understanding of these issues will lead to safer and more cost effective $CO_2$ sequestration.
Multiphase transport in heterogeneous and deformable media: Gravity segregation, viscous fingering, and preferential flow along high permeability pathways will play a dominant role in $CO_2$ migration in the subsurface. These complexities will be compounded by deformation accompanying adsorption/desorption

processes and precipitation/dissolution processes. A better fundamental understanding is needed to predict migration of $CO_2$ and to optimize the sweep efficiency in geologic formations.

$CO_2$ dissolution and reaction kinetics: While the principle reaction pathways between $CO_2$ and sedimentary formations are relatively well understood (e.g. reactions of feldspars with acid to form calcite, dolomite, siderite and clay, dissolution of carbonate minerals; dissolution of carbonate minerals), the kinetics of $CO_2$ dissolution in the liquid phase and subsequent rock/water reactions are slow and poorly understood. If conversion of $CO_2$ to these stable mineral phases is to be an important component of sequestration in aqueous formations, understanding of the kinetics of these reactions and the processes controlling them is essential.

Micromechanics and deformation modeling: Injection of $CO_2$ into geologic formations such as active oil and gas reservoirs will be accompanied by deformation in the region close to the injection well. In brine formations, deformation is likely to be widespread because injection will not be accompanied by fluid withdrawal (as is the case for value-added sequestration strategies such EOR). In this case the pressure buildup may be distributed over a broad area. The effects of local and regional deformation and the effects of this on caprock integrity, leakage and induced seismicity must be evaluated.

Coupled H-M-C-T (Hydrologic-Mechanical-Chemical-Thermal) processes and modeling: Accurately predicting, assessing, optimizing and confirming the performance of sequestration project requires an accurate coupled model of all of the processes that influence the repository performance and safety. While much experience in subsurface simulation has been gained from the oil and gas industry, and the groundwater management and remediation industries, experience shows that the quality of our predictions depends strongly on having a simulator geared toward the specific application. Simulators tailored to the specific physical and chemical processes important for $CO_2$ sequestration must be developed, tested, calibrated and refined through operational experience. This is particularly true for assessing the long-term (> 100 years) sequestration of $CO_2$ in geologic formations.

High resolution geophysical imaging: High resolution geophysical imaging has the best potential for cost-effective monitoring of the migration and byproduct formation of $CO_2$ in subsurface environments. Three dimensional and 4-dimensional (time-lapse) images of geologic structures and pore-fluids can be created with surface, surface to borehole and cross borehole techniques. The resolution needs to be improved if these methods are relied on to detect caprock leakage, formation of viscous fingers and preferential pathways.

**The Need for Additional Pilot Projects**

The need to begin additional pilot projects now has been a recurring theme throughout the R&D planning activities. Industry leaders, academic and national laboratory researchers, and federal research managers all agree that pilot testing, conducted with the full complement of scientific tools to predict, monitor, and verify performance and to assure public safety, is an essential next step. Unlike some of the other sequestration technologies that will require years to decades of fundamental and applied R&D before they are ready to be implemented, geologic sequestration is poised for early application. The experiences at Sleipner Vest, at Weyburn, and in the San Juan Basin attest to the practicality of this approach. A set of scientifically conducted and monitored pilot tests, in each of the different formations being considered for sequestration, is critically needed to sustain the momentum required to build confidence, accelerate development, and ready this technology for application.

**The Need to Engage the Public**

Over the past several decades, we as a society have learned that engaging the public early and in a meaningful way is a prerequisite to the acceptance of new technologies, particularly those technologies with potential environmental or economic impacts. Without significant involvement, the public will neither understand the need for geologic sequestration nor willingly accept the costs and potential risks associated with it. Educational and informational materials will need to be developed and disseminated. Applied R&D projects and pilot testing provide the opportunity to get early public involvement, through the development and dissemination of information and educational materials. More substantial involvement can be obtained by inviting members of the public to serve on advisory and review committees. Developing an understanding of the full range of concerns about geologic sequestration at the beginning of the technology development cycle will enable development and demonstration of monitoring and verification methods that will increase public confidence and build a basis for acceptance of this technology.

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